Frequency Selective Surface based Metamaterial for Radio Communication

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Abstract

Metamaterials are composed of periodic metals on dielectric substrate that exhibiting properties which are not found in the nature. In this paper, we have pointed a 2.15 GHz wide bandwidth frequency selective surface based single layer metamaterial for C-band applications, which is consisted of ring resonators and the size of a single unit cell is 11×11 mm^2 and the effective medium ratio is 5.27. Commercial available CST Microwave Studio electromagnetic simulator tool is used to design and numerical analysis. The numerical and the experimental results are around overlapped together. The measured transmittance (S_{21}) shows the resonance in 5.17 GHz, whereas the simulated resonance in 5.26 GHz. Besides, the proposed design is explained by the equivalent lumped element circuit model and exhibits left handed characteristics from 6.35 to 7.72 GHz in the microwave frequency region.

Keywords: C-band, Left-handed characteristics, Metamaterial.

1. Introduction

Frequency selective surface (FSS) structures with multi pole characteristics have been widely investigated in the microwave and millimeter-wave frequencies of the spectrum [1]. It has been used extensively in the last few decades in various applications. Currently, frequency selective surfaces based on metamaterials are increasingly important in microwave technique for the advanced applications [2]. Moreover, metamaterials are artificial material with more compact size compare with conventional structures and have some infrequent properties, which does not exist in nature materials. Due to these unique properties, like negative refractive index, negative permeability, left handed characteristics, chirality, and so on. This artificial material has been received great attention in the physics and engineering communities. Due to their unique benefits, metamaterials have provided many important effects, such as, absorption, antenna performance enhances, invisible cloaking, energy harvesting, SAR reduction, filter application, etc. EM-metamaterial were first visionary speculated by the Russian Physicist Victor Veselago in 1967. Later after a long time, in 2000, Smith and his colleagues introduced a material that shown simultaneously negative permittivity and permeability with some exceptional characteristics in microwave frequency range by combined the finite section of the negative permeability material with a negative permittivity material [3]. Further, a metamaterial was developed by capacitor loaded strips and split ring resonators in 2003 by R. W. Ziolkowski, which exhibited negative permittivity and negative permeability both at the X-band frequencies [4]. At present, for the rapid growth of the modern telecommunication systems the demand of high performances, larger bandwidth, sharp current distribution, and multiband resonance, compact in size has been increased exponentially. A compact z-shaped double negative metamaterial was exhibited for dual band application [5]. The dimension of the designed DNG metamaterial was 10×10 mm^2 and effective medium ratio was 4.0. In 2017 a z-shaped double negative metamaterial, which has wide bandwidth was presented in [6]. The dimension of the metamaterial single unit cell was 10×10 mm^2 and applicable for S-, C-, X- and Ku-band applications and analysed at different azimuthal angles like, $\pi/12$, $\pi/6$, $\pi/4$, $\pi/3$, $5\pi/12$, and $\pi/2$. Further, Xu et al. introduced a left-handed metamaterial had multiband based on the three split ring resonators. The splits rings was designed on the both side of the dielectrics substrate material and double layer. The unit cell was applicable for C- , X-band and effective medium ratio was 7.0 in 2012 [7]. A Z-shaped meta-atom working in only a single band with a single negative property was suggested by Dhouibi et al. in 2012 [8]. In 2017, Hasan et *al.* projected a negative index meta-atom, resonance at C-, X- and Ku-band with wide NRI bandwidth from 7.0 to 12.81 GHz [9]. Sarkhel et al. exhibited a compact dual band metamaterial that designed as "delta-shape" and applicable for C-band. The dimensions of the delta shape unit cell were 7.40×7.40 mm^2 and the effective medium ratio was 7.50 in 2015 [10]. In addition, Islam et *al.* proposed a 30×30-mm^2 'H-shape' metamaterial for multi band operations and the resonance peaks were found in S-, C-, X- and Ku- frequency band in 2014. Additionally, the H-shape structure also exhibited double negative characteristics, but the effective medium ratio was 3.64 [11]. In 2015, Zhou et *al.* presented an 8.5×8.5-mm^2left-handed metamaterial via coplanar electric and magnetic resonators, and the effective medium ratio was 4.80. The 'double Z-shape' resonator structure was composed of two orthogonal Z-shape metal strips, and displayed resonance in7.3, 8.1, and 9.4 GHz [12]. In 2016, Yang et *al.* demonstrated a 5×5-mm^2‘Ring-shape’ meta-atom for wearable, flexible and stretchable microwave meta-skin, with cloaking effect from 8.0 to 13.0GHz and the effective medium ratio was 6.0 [13]. In 2016, Liu et *al.* introduced a 5×5-mm^{2}split ring-shape left-handed metamaterial, which was developed by modified circular electric resonators, and it exhibited dual-band with the effective medium ratio of 5.45 [14].

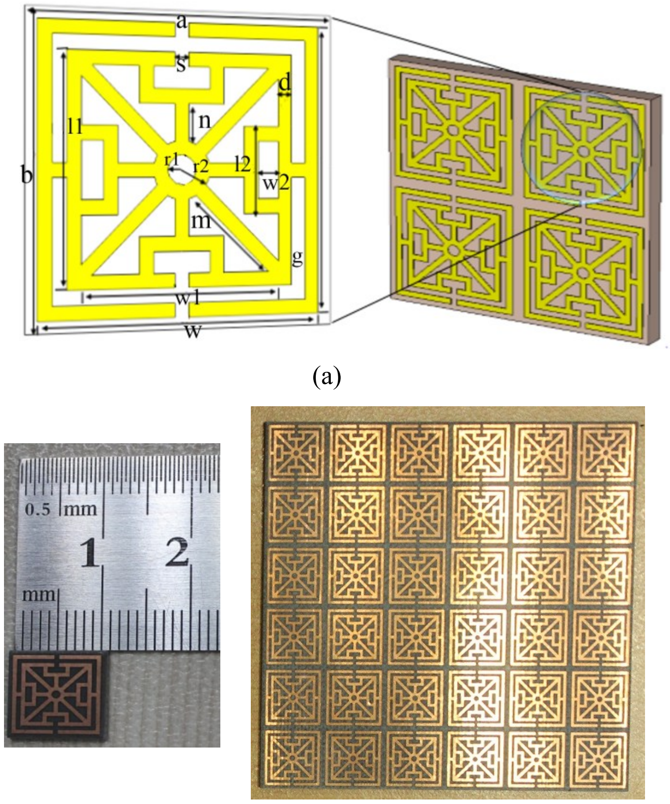
In this paper, a hybrid and miniaturized metamaterial that is composed by the combination of two split ring resonator with metal strips in the inner ring resonator is presented. The designed metamaterial is investigated for the radio communication, since the structure is applicable for C-band application. For the experimental validation a periodic array of unit cell is fabricated and measured. The measured transmittance shows the resonance in 5.17 GHz, whereas the simulated resonance in 5.26 GHz. Due to effective medium ratio 5.27, the proposed metamaterial is compact in size and potential for practical radio telecommunication application. Further, the effect on resonance frequency by different types of substrate materials is also investigated in this paper. The paper is oriented as follows, metamaterial design methodology with the procedure of revival effective medium parameters are explained in section 2, lumped circuit model of equivalent circuit for designed metamaterial describes in section 3, section 4 shown the analysis of the results, and the paper is concluded by section 5.

2. Design of the Metamaterial and Methodology

The proposed metamaterial structure is composed by combining the two ring resonator with an arrangement of splits and metal strips in the inner ring resonator. All the design, simulations and investigation are obtained through the computer simulation technology Microwave Studio electromagnetic simulator tool. A 1.575-mm thick (t) Rogers RT 5880 substrate (dielectric constant of 2.20 and tangent loss of 0.0009) is used as the host medium, while a single unit-cell dimensions are set to 11 mm, 11 mm, and 0.035 mm along the respective (*x,y,z*) axes. The structure is excited by a uniform plane wave propagating toward the z-direction, with its electric and magnetic fields are polarized respectively along the *x*- and *y*-axis (shown in figure 2(a)). Moreover, table 1 shows the design specification of the proposed metamaterial single unit cell structure, where the substrate material length, width and height are respectively, ‘a’, ‘b’, and ‘t’. The metallic strips width (d) and height (h) are 0.50 mm and 0.035 mm. the splits (s) and the length and width of the inner and outer ring resonators are respectively, ‘l1’, ‘w1’, ‘l’ and ‘w’. However, figure 1 shows the schematics view, fabricated view of proposed metamaterial single unit cell and array structure.

Table 1: Configurations of the FSS metamaterial unit cell.

Parameters	a	b	l	w	l1	w1
Dimensions (mm)	11	11	10	9.0	8.0	7.0
Parameters	d	s	m	n	l2	r2
Dimensions (mm)	0.5	0.25	4.0	1.2	3.0	1.0



(a)

(b) (c)

Figure 1: Proposed FSS Metamaterial: (a) Schematic structure, (b) Fabricated single unit cell structure, (c) Fabricated array structure.

The electromagnetic properties of the proposed metamaterial are characterized numerically by using finite integration technique based CST Microwave Studio package. A single unit cell is examined with appropriate boundary conditions, where perfect electric and perfect magnetic boundaries are applied along x and y planes, so that electric field is oriented along x-direction and magnetic field is oriented along y-direction shown in figure 2(a). It also indicates that unit cells are repeated in the direction of the periodicity. In addition, the EM-waves are incident on the designed metamaterial along the z-direction. The extraction of the necessary effective parameters and the normalized characteristic impedance of the medium is achieved form equation (1-11) and continuity of the refractive index in the frequency domain is iteratively achieved [15]. However, the effective medium parameters can be extracted from,

$$\eta = \frac{1}{kd}\cos^{-1}\left[\left\{\frac{1}{2S_{21}}\left(1 - S_{11}^{2} + S_{21}^{2}\right)\right\} \pm \frac{2m\pi}{kd}\right] \qquad 1$$

$$Z = \pm\sqrt{\frac{\left(1+S_{11}\right)^2 + S_{21}^2}{\left(1-S_{11}\right)^2 + S_{21}^2}} \qquad 2$$

$$S_{11} = \left\{\frac{R_1\left(1-e^{-2j\theta}\right)}{1-R_1^2 e^{-2j\theta}}\right\} \qquad 3$$

$$Similarly, S_{21} = \left\{\frac{e^{-2j\theta}\left(1-R_1^2\right)}{1-R_1^2 e^{-2j\theta}}\right\} \qquad 4$$

where, $\theta = \zeta d$ and ζ is the propagating constant. However, T is defined as exponential transmission.

$$T = e^{-2j\theta} = \left\{\frac{S_{21}+S_{11}-R_1}{1-R_1\left(S_{21}+S_{11}\right)}\right\} \qquad 5$$

$$Similarly, R_1 = \left\{\frac{T-S_{21}+S_{11}}{1-T\left(S_{21}+S_{11}\right)}\right\} \qquad 6$$

$$Permittivity, \varepsilon_{eff} = \left(\frac{\eta}{Z}\right) \qquad 7$$

$$Permeability, \mu_{eff} = \left(\eta \times Z\right) \qquad 8$$

$$k \approx \frac{1}{jd} \times \left[\frac{\left(1-S_{21}-S_{11}\right)\left(1+R_1\right)}{1-R_1\left(S_{21}+S_{11}\right)}\right] \qquad 9$$

$$k \approx \frac{2\pi f}{c}\sqrt{\varepsilon_r \mu_r} \approx k_0\sqrt{\varepsilon_r \mu_r} \qquad 10$$

$$\eta_{eff} \approx \left(\frac{k}{k_0}\right) \approx \frac{2}{jkd}\left[\left\{\frac{\left(S_{21}-1\right)^2 - S_{11}^2}{\left(S_{21}+1\right)^2 - S_{11}^2}\right\}\right]^{1/2} \qquad 11$$

3. Lumped Element Circuit Model

The increase in the number of split rings will increase the number of split gaps and metallization on the substrate; thus, an increase in the surface electric field will be observed on the split gap areas and overall surface of the unit cell. The increasing values of overall capacitance, which includes gap and surface capacitance, will reduce the operating frequency as they are inversely proportional to each other. A simple lumped element circuit can represent the analogy of the split ring resonator. The split rings form the magnetic inductance and can be considered as inductors. The capacitance is mainly formed in and around split gap areas. The split ring resonator exhibit electromagnetic resonance when the electric energy stored in capacitor; i.e., gap is in balance with the magnetic energy stored in the inductors, i.e., split rings. The changes in capacitance, *C* and inductance, *L* due to dielectric loading from biomolecule leads to a considerable shift in the frequency of resonance. Moreover, equation (12-13) is developed for calculated the resonance peaks from the total inductance and capacitance which is formed in the lumped circuit model for the proposed design metamaterial structure by follow the ref. [16]. In addition, from the developed equations (12-13) the resonance frequency is around at 5.1 GHz, whereas the simulated resonance is at 5.26 GHz and the measured resonance is around at 5.17 GHz. Therefore, the total inductance of the designed structure can be determined from the equation given as follows,

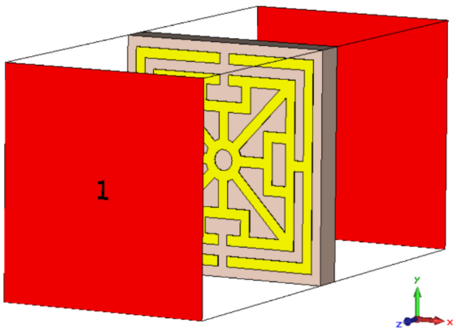
$$L_T \approx \mu_0 t\left\{\frac{\left(a+b+s\right)^2+\left(m+n+d\right)^2}{\pi\left(l+w\right)\left(l_1+w_1\right)} + \frac{\sqrt{l_1^2+l_2^2+b^2}}{\sqrt{w^2+w_1^2+a^2}}\right\} \qquad 12$$

In addition, the total capacitance can be calculated from,

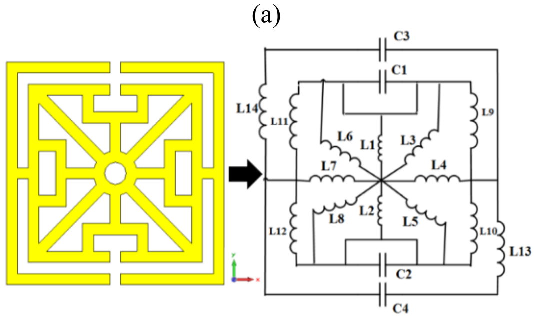
$$C_T \approx \varepsilon_0 t\left[\frac{\sqrt{l^2+l_1^2+m^2}}{\sqrt{d^2+s^2}} - \ln\left\{\frac{\left(a+b\right)^2}{\pi\left(w_1^2-m^2-n^2\right)}\right\}\right] \qquad 13$$

where 'd' is the thickness of the substrate, '*Z*' is the normalize impedance, '*k*' is the wave vector, 'R_1' is the sample interface, '*C*' is the velocity of light, 'S_{11}' is the reflection coefficient, and 'S_{21}' is the transmission coefficient. Besides, free-space permeability is $4\pi\times10^{-7}$ H/m and the permittivity is 8.85×10^{-12} F/m. So, the resonance frequency would be,

$$Resonance\ Frequency, f_r = \frac{1}{2\pi\sqrt{L_T C_T}} \qquad 14$$



(a)

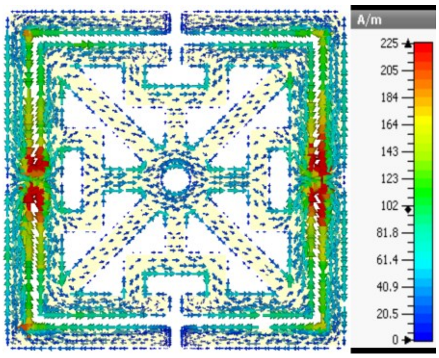


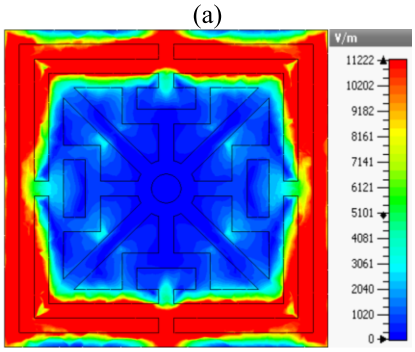
(b)

Figure 2: (a) Boundary condition in simulation, and (b) Lumped equivalent circuit model of the proposed FSS metamaterial single unit cell structure.

4. Result Analysis

The proposed metamaterial has been made of rectangular split ring resonators and arranged periodically to form of metamaterial cluster. For attaining stable magnetic and electric field response from the mentioned metamaterial based on meta-atom cluster, incidence external field has been utilized. In order to realize the transmission spectra of the meta-atom unit cell, incidence direction is horizontal to the meta-atom unit cell surface plane. When the long edges of the structure are parallel to the electric field polarization, electric response has been induced with the incident waves. When a loop is existed in the split ring resonators structure, for inducing the magnetic response, the parallel incident waves are comfortable. From the surface current distribution, it is realized that the lumped resonance is very stable and the electric field is a dominant figure on the inner ring and the outer ring with capacitive gap area indicated in figure 3(b-c). The concentration of the surface current is around the split gap due to having raised capacitance. The current flows entirely the metamaterial including the split gap area in figure 3(a).


(a)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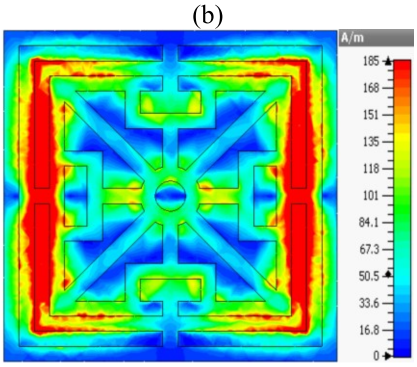

(c)

Figure 3: (a) Surface current distribution, (b) Electric field, and (c) Magnetic field of the proposed FSS metamaterial unit cell at 5.26 GHz.

In order to demonstrate the performance of the metamaterial, the proposed structure is measured and the measured and the simulated results are well matched and a slight discrepancy in the results is due to the fabrication process of the structure shown in figure 4. The measured transmittance shows the resonance in 5.17 GHz, which is in the C-band and the amplitude of the resonance point is 26.0 dB. In addition, the simulation results of the transmittance (S_{21}) is also shown in the figure 4, where the resonance point in 5.26 GHz and the magnitude of the resonance point is 43.0 dB. Moreover, in the simulated and measured results the proposed metamaterial shows the same resonance frequency band for linear polarization, and can be altered the resonance frequency by the parallel polarization, but completely fixed for linear polarization (shown in Figure 4). However, the designed metamaterial can maintain a symmetric current path (displayed in figure 3(a)) for linear polarization.

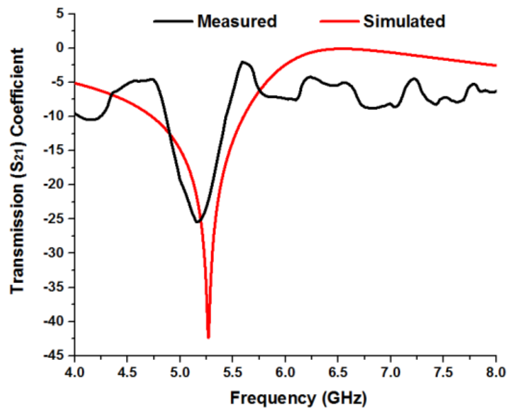
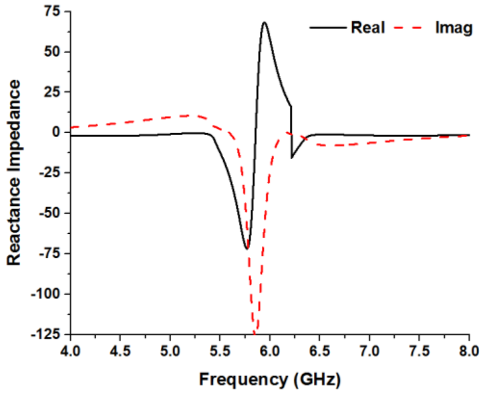
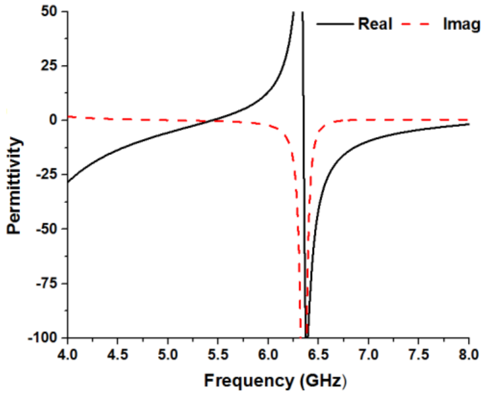


Figure 4: Measured and simulated transmittance of the proposed FSS metamaterial.

The surface (reactance) impedance and the effective permittivity, permeability, refractive index of the designed metamaterial is exhibited in figure 5(a-d). From figure 5(a) the impedance at 5.81 GHz is (-58.44-99.0j). The permittivity curve shows two negative frequency ranges. The first one is from 4.0 to 5.44 GHz, while the second one is from 6.35 to 8.0 GHz. Further, the permeability displays negative regime from 5.86 to 8.0 GHz. which covers around 2.14 GHz. Moreover, negative refractive index is achieved at two frequency ranges, where the first one is from 4.0 to 5.22 GHz and the last one is from 5.57 to 7.72 GHz, shown in figure 5(b-d). However, the effective permittivity, permeability and refractive index curves show real magnitude of negative values from 6.35 to 7.72 GHz. According to the left handed characteristics, if the permittivity and permeability are simultaneously negative, then the refractive index will be negative. As a result, the designed structure can be called as a left handed metamaterial for any frequency points in the microwave frequency range from 6.35 to 7.72 GHz. Such as, at 6.43 GHz the real magnitude of the effective permittivity, permeability and refractive index are respectively, -68.27, -42.01, and -54.67.



(a)



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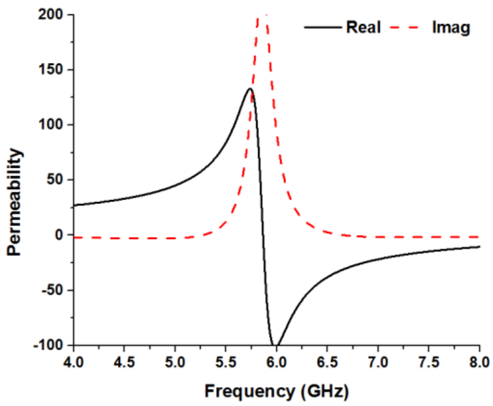

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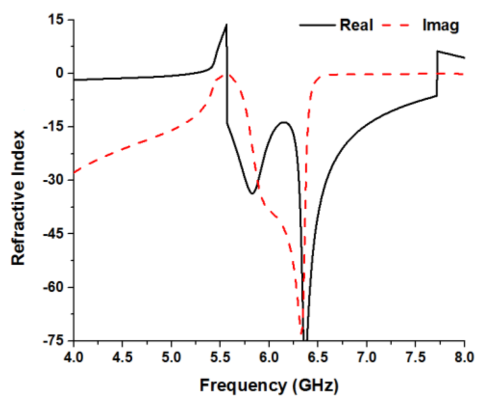


(d)

Figure 5: Amplitude of the proposed FSS metamaterial, (a) Reactance impedance, (b) Permittivity, (c) Permeability, (d) Refractive index.

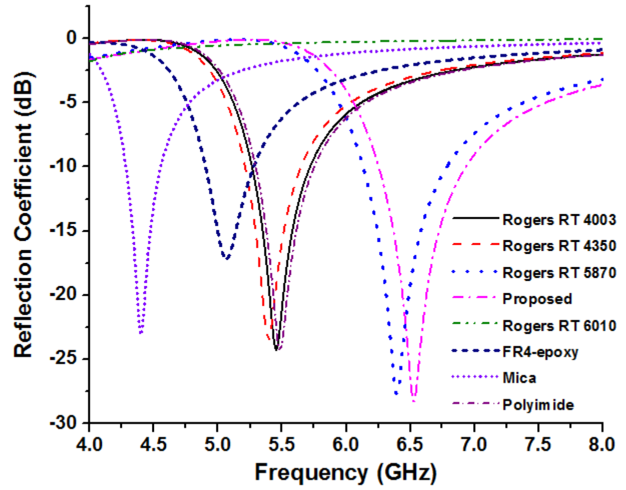
Figure 6 represents the effect on the resonance frequency through various types of materials by using as a substrate material. The dielectric constant of the FR-4, Rogers RT 5880, Rogers RT 5870, Rogers RT 6010, Rogers RT 4350, Rogers RT 4003, Mica, and Polyimide are respectively 4.50, 2.20, 2.35, 10.70, 3.66, 3.55, 5.70, and 3.50. Besides, the tangent loss of the above materials is respectively, 0.002, 0.0009, 0.0012, 0.0023, 0.0037, 0.0027, 0.0, and 0.008. If the dielectric constant is increased, then substrate material conductivity is decreased. The permittivity of a material depends on the material internal structure. When the EM-waves are propagated through a material, then the electric and magnetic fields are oscillating as sinusoidal pattern and the velocity of the atoms depend upon the conductivity, whither the conductivity depends on the internal structure. In addition, the internal pattern, permittivity, polarization, etc. caused the variation in the results of the reflection (S_{11}) and transmission (S_{21}) coefficients. Table 2, show the dielectric constant and loss of tangent of different substrate materials.

Table 2: Dielectric materials for the proposed FSS metamaterial analysis.

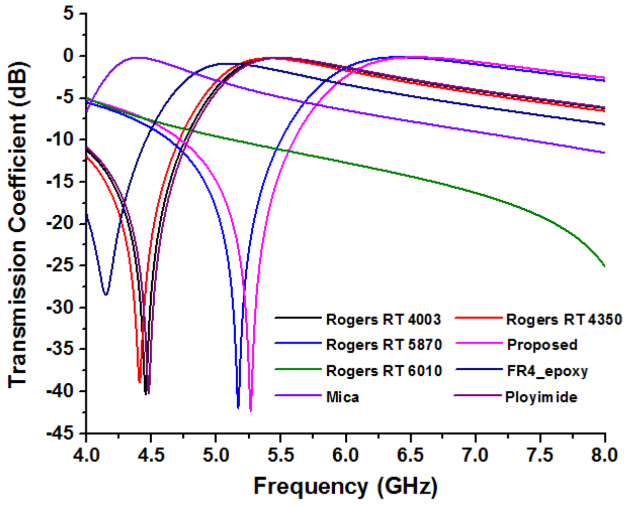
Substrate Material	Permeability	Permittivity	Loss Tangent	Resonance in (S_{21})
Proposed	1.0	2.20	0.0009	5.26
Rogers RT 5870	1.0	2.35	0.0012	5.17
Polyimide	1.0	3.50	0.008	4.48
Rogers RT 4003	1.0	3.55	0.0027	4.45
Rogers RT 4350	1.0	3.66	0.0037	4.40
FR-4	1.0	4.50	0.002	4.15
Mica	1.0	5.70	0.0	4.02
Rogers RT 6010	1.0	10.70	0.0023	>4.0

The transmittance resonance depends on the permittivity of the substrate material. If the permittivity is increased, then the resonance peaks are shifted toward the lower frequency. From figure 6(a-b), with the resonance peaks are sifted towards the lower frequency with the use of larger value of permittivity material used as substrate of the proposed structure. Moreover, from figure 6(b) and table 2, the resonance peaks of the substrate material are respectively, 5.26 GHz (magnitude of -42.34 dB), 5.17 GHz (magnitude of -41.95 dB), 4.48 GHz (magnitude of -40.19 dB), 4.45 GHz (magnitude of -40.28 dB), 4.40 GHz (magnitude of -38.88 dB), 4.15 GHz (magnitude of -28.46 dB), 4.02 GHz (magnitude of -6.02 dB), and less than 4.0 GHz for sequentially Rogers RT 5880 (permittivity of 2.20), Rogers RT 5870 (permittivity of 2.35), Polyimide (permittivity of 3.50), Rogers RT 4003 (permittivity of 3.55), Rogers RT

4350 (permittivity of 3.66), Epoxy Resin Fibre (FR-4) (permittivity of 4.50), Mica (permittivity of 5.70), and Rogers RT 6010 (permittivity of 10.70). The shift of the resonance frequency can be explained by the overall capacitance changes of the resonator. Increasing the dielectric constant causes an increase for each capacitance values between the ground plane and resonator.



(a)



(b)

Figure 6: (a) Reflection (S_{11}) coefficient, (b) Transmission (S_{21}) coefficient of the proposed metamaterial printed on different substrate material.

The effective medium ratio (EMR) of a medium is based on the properties and the relative fractions of its components and can be derived from the calculation of *(λ/a)*, where, '*λ*' is the wavelength and 'A' is the dimension of the proposed meta-atom structure. In table 3, the proposed metamaterial exhibits the EMR is 5.27 and resonance in C-band in microwave frequency, which means the designed structure is miniaturized in size and applicable for radio telecommunication applications.

Table 3: Comparison of the designed structure with the reported researches.

References	Dimensions (mm^2)	Frequency Band	EMR *(λ/a)*
Islam et *al.*[11]	30×30	Multi Band	3.64
Zhou et *al.*[12]	8.5×8.5	X-Band	4.80
Liu et *al.* [14]	5.0×5.0	X-Band	5.45
Proposed FSS Metamaterial	11×11	C- Band	5.27

5. Conclusions

We have proposed a FSS metamaterial to achieve high performance and easy to fabricate and practically applicable. The structure is composed of electric and magnetic resonators and the measured and simulated results are overlapped each other. Due to the effective medium ratio 5.27, the compact metamaterial practically applicable for C-band application. The equivalent lumped element circuit model of the proposed metamaterial is design, where the inductance and the capacitance are formed by the metal part and the splits, respectively of the proposed structure. Finally, the substrate material effects on the performance of the designed metamaterial structure is also investigated, whereas the permittivity of the substrate material is inversely proportional with the resonance peaks of the proposed metamaterial.

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